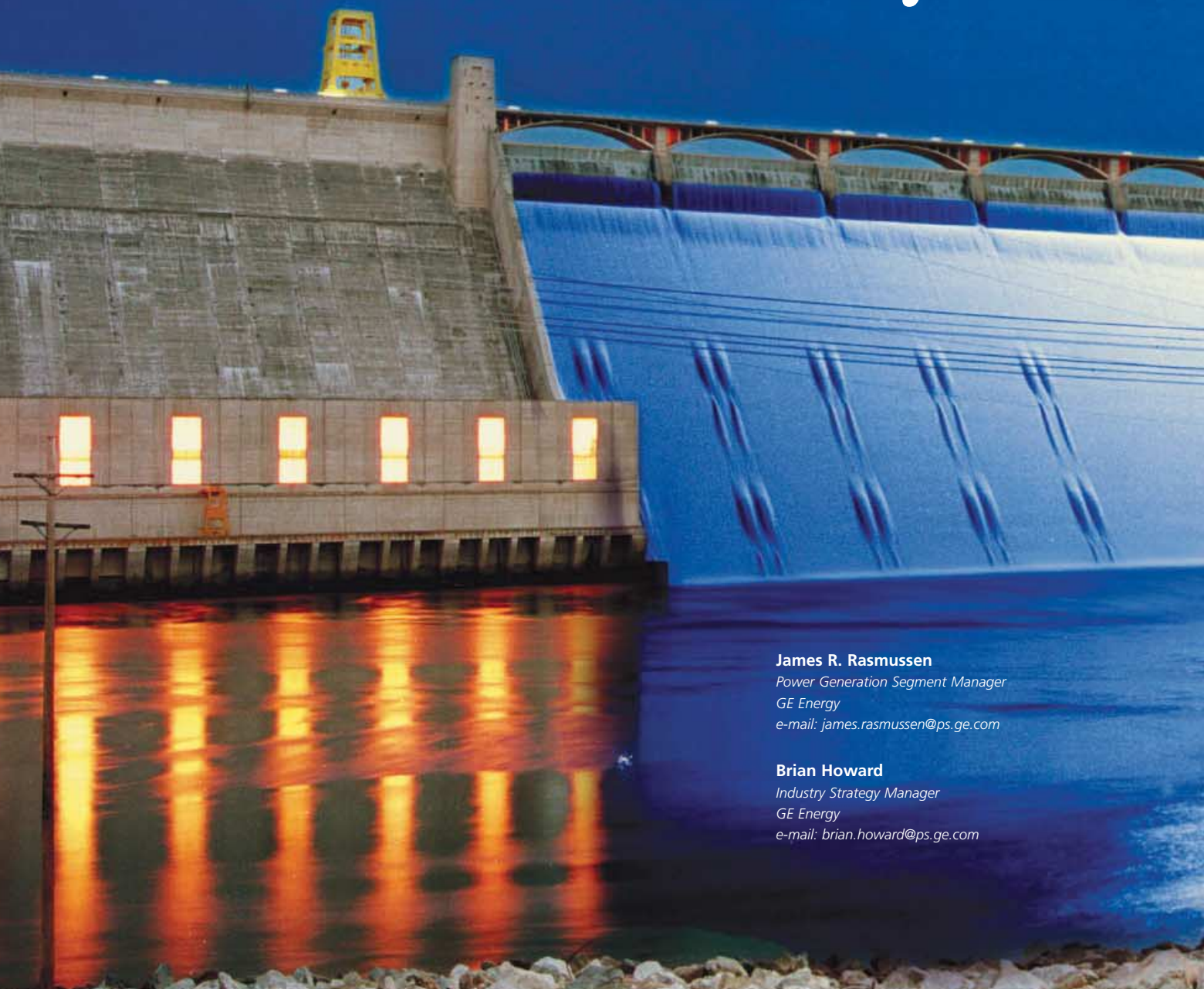
Condition Monitoring for Hydro Machinery



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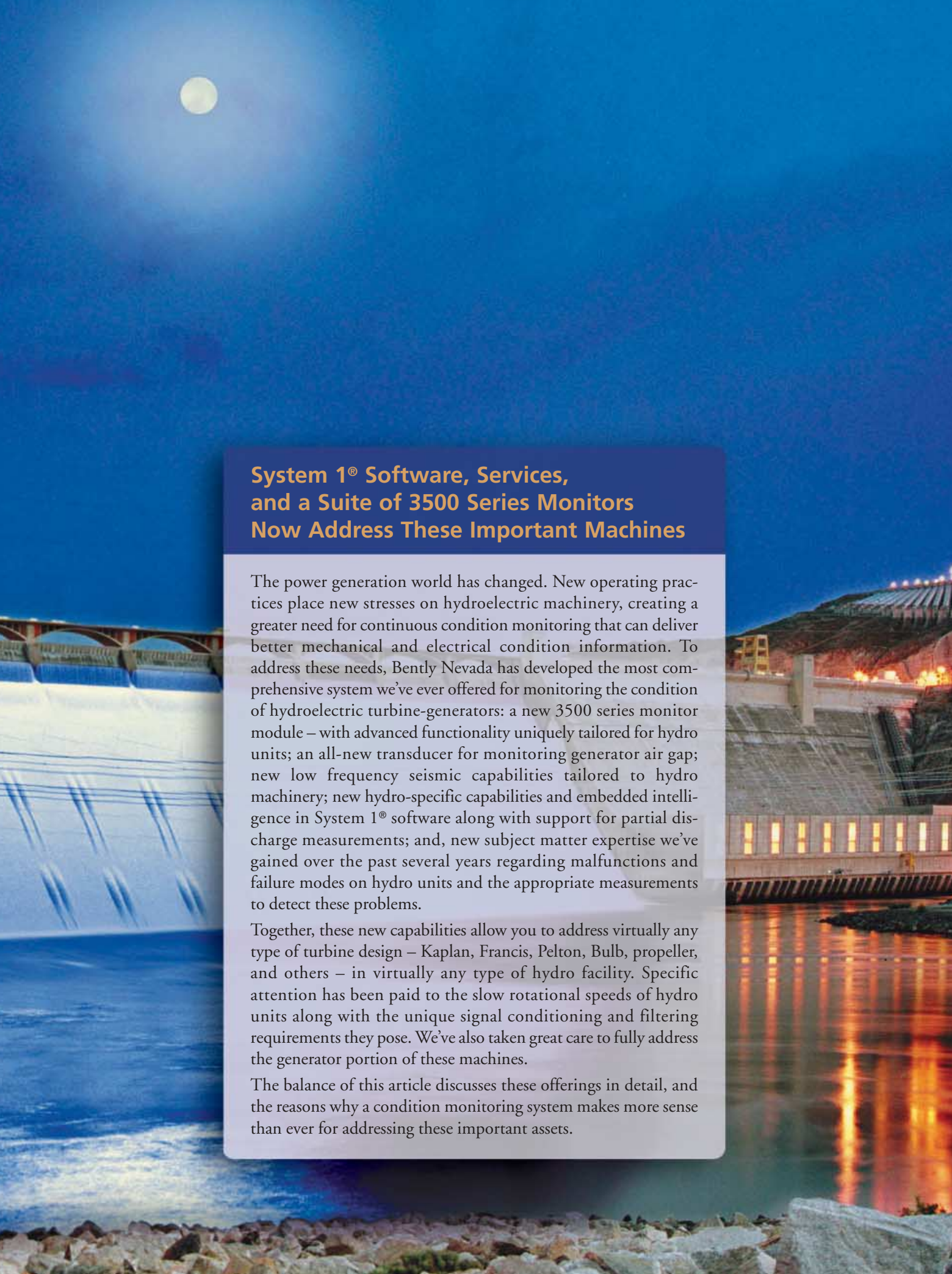


System 1® Software, Services, and a Suite of 3500 Series Monitors Now Address These Important Machines

The power generation world has changed. New operating practices place new stresses on hydroelectric machinery, creating a greater need for continuous condition monitoring that can deliver better mechanical and electrical condition information. To address these needs, Bently Nevada has developed the most comprehensive system we've ever offered for monitoring the condition of hydroelectric turbine-generators: a new 3500 series monitor module – with advanced functionality uniquely tailored for hydro units; an all-new transducer for monitoring generator air gap; new low frequency seismic capabilities tailored to hydro machinery; new hydro-specific capabilities and embedded intelligence in System 1® software along with support for partial discharge measurements; and, new subject matter expertise we've gained over the past several years regarding malfunctions and failure modes on hydro units and the appropriate measurements to detect these problems.

Together, these new capabilities allow you to address virtually any type of turbine design – Kaplan, Francis, Pelton, Bulb, propeller, and others – in virtually any type of hydro facility. Specific attention has been paid to the slow rotational speeds of hydro units along with the unique signal conditioning and filtering requirements they pose. We've also taken great care to fully address the generator portion of these machines.

The balance of this article discusses these offerings in detail, and the reasons why a condition monitoring system makes more sense than ever for addressing these important assets.

MONITORING WHY

TABLE 1 >>

Historically, hydro machines have had the lowest cost per MW on the grid. System operators would base load these units, only reducing load or removing the units from service when maintenance was required, the power was not needed, or stream flow conditions dictated removal from service. In this base-load mode of operation, a typical large hydro machine could operate successfully for over 40 years with only routine scheduled maintenance and minimal condition monitoring.

In today's world of partially deregulated utilities and grid systems where fish and water issues often eclipse energy issues, the operating flexibility of hydro machines has led those same 40-year-old units to be the load-follow units with continuous load changes and partial load operation. In some cases, such machines are cycled on- and off-line *eight to ten times per day*. Pump/storage applications can experience even more starts and stops, often representing the most extreme operating conditions of all hydro units.

However, running a unit at partial load brings into play operational considerations like rough load zone and cavitation, along with operation that is far from the unit's peak efficiency. Further, continuous speed and load cycling introduce thermal, mechanical, and electrical stresses on the machinery that may not have even been considered in the original design. At the same time, normal scheduled maintenance outages are being reduced or eliminated.

Clearly, it's just not the same world for hydro units, and the circumstances that often allowed these units to operate virtually trouble-free for decades no longer apply. Today's operating realities are introducing a host of factors that preclude a status-quo approach to condition monitoring, maintenance, and asset management.

A properly engineered condition monitoring system can help the hydro operator avoid operating the machine in load zones where vibration or cavitation can cause premature damage. In addition, the system can provide early warning of impending failures allowing time to schedule maintenance outages and make repairs before small problems become large ones. The system will also provide the operator with sufficient information to make intelligent decisions regarding maintenance planning, thus allowing maintenance to be performed only when conditions necessitate.

MONITORING WHAT

A monitoring system for hydro turbine-generators – as for any other type of machine – must first consider the types of machinery malfunctions that must be detected and the types of machinery health information that must be supplied in order to adequately manage the asset. Table 1 summarizes this information along with the corresponding measurements required.

Table 1

Malfunctions and Corresponding Measurements

MALFUNCTION[1]	MEASUREMENT												
	Guide Bearing Vibration (Runout)[2]	Thrust Bearing Oil Film Thickness[2]	Guide Bearing Temperature[2]	Thrust Bearing Temperature[2]	Keyphasor® Pulse	Head Cover/Draft Tube Vibration	Generator Air Gap	Stator Frame Vibration	Generator Temperatures	Process Variables	Generator Partial Discharge	Wicket Gate Position	Seal Ring/Blade Tip Clearance[4]
	■ ▲ ★	■ ▲ ★	■ ▲ ★	■ ▲ ★	■ ▲ ★	▲ ★	▲ ★	▲ ★	▲ ★	▲ ★	★	★	See Note 4
Mechanical Unbalance	● (Direct, 1X)				●								
Electrical Unbalance	● (Direct, 1X)				●								
Hydraulic Unbalance	● (Direct, Shaft CL, 1X, NX)				●								
Rough Load Zone	● (NOT 1X)				●					●		●	
Shear Pin Failure	● (Shaft CL, NX)	●			●					●			
Misalignment	● (Direct, Shaft CL, 1X)				●								
Cavitation						●				●		●	
Seal Ring/ Discharge Ring Distortion[3]					●								●
Excessive Turbine Vibration[3]					●								●
Bearing Overload	●	●	●	●									
Bearing Fatigue	●	●	●	●									
Insufficient Bearing Lubrication	●	●	●	●									
Stator Insulation Deterioration											●		
Stator Winding Vibration											●		
Rotor Rim Movement					●		●						
Stator Core Shifts					●		●	●					
Uneven Air Gap					●		●	●					
Stator/Rotor Out of Round					●		●	●					
Stator/Rotor Concentricity					●		●	●					
Stator Flexing					●		●	●					
Loose Stator Laminations								●					
Unbalanced Air Gap Forces					●		●	●					
Plugged Stator Coolers									●				
Blocked Stator Ventilation Ducts									●				
Overheated Stator Coils									●				

1 Detection of a particular malfunction requires all of the measurements checked in that row.

2 These parameters are recommended for auto-shutdown machinery protection.

3 Francis, Kaplan, or Propeller-type runners only.

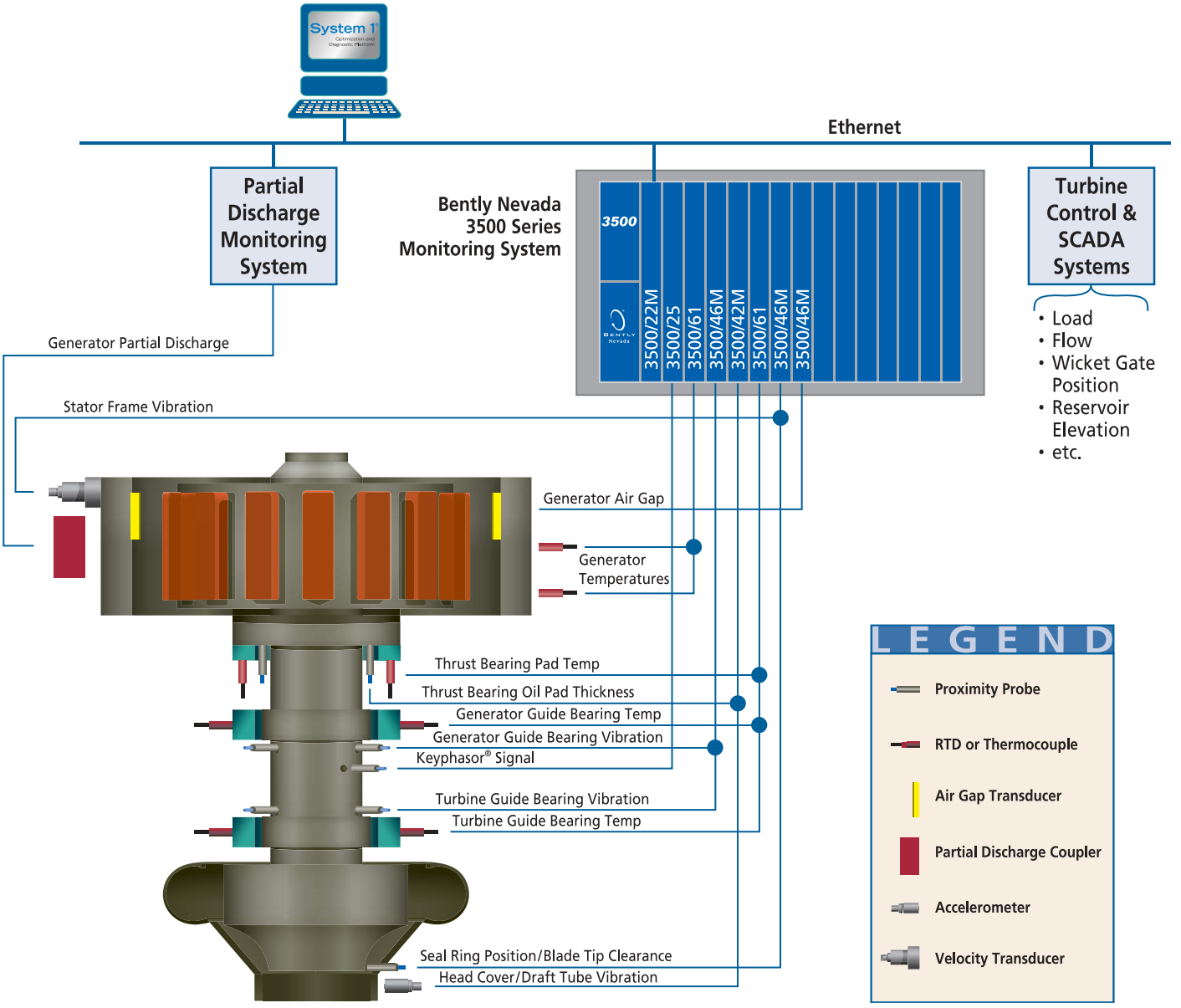
4 This measurement is recommended on a case-by-case basis, subject to customer condition monitoring needs, equipment condition, and turbine construction constraints.

■ Minimal System – Measurements required for basic safety shutdown when catastrophic failure occurs, limited condition monitoring and proactive capabilities.

▲ Basic System – Measurements required for basic protection with moderate condition monitoring and proactive capabilities.

★ Recommended System – Measurements required for optimal protection and condition monitoring, full proactive capabilities.

FIGURE 1


System 1
Ethernet
Partial Discharge Monitoring System
Bently Nevada 3500 Series Monitoring System
3500
3500/22M
3500/25
3500/61
3500/46M
3500/42M
3500/61
3500/46M
3500/46M
Turbine Control & SCADA Systems
• Load
• Flow
• Wicket Gate Position
• Reservoir Elevation
• etc.
Generator Partial Discharge
Stator Frame Vibration
Generator Air Gap
Generator Temperatures
Thrust Bearing Pad Temp
Thrust Bearing Oil Pad Thickness
Generator Guide Bearing Temp
Generator Guide Bearing Vibration
Keyphasor® Signal
Turbine Guide Bearing Vibration
Turbine Guide Bearing Temp
Seal Ring Position/Blade Tip Clearance
Head Cover/Draft Tube Vibration
LEGEND
Proximity Probe
RTD or Thermocouple
Air Gap Transducer
Partial Discharge Coupler
Accelerometer
Velocity Transducer

MONITORING HOW

For each of the measurements in Table 1, Bently Nevada can now provide an integrated monitoring solution that is fully compatible with System 1 software. Table 2 on the following page summarizes the appropriate transducers and monitoring modules; Figure 1 at left shows the arrangement of these transducers on a typical vertical unit.

3500/46M Hydro Monitor

Hydroelectric turbine-generators are subject to forces and operating conditions unique to their operation and configuration. They typically operate at low rotational speeds, usually from 60 to 600 rpm, and are physically very large, often with generator rotors that may be more than 50 feet in diameter and weigh more than 1,000 tons. Their physical mass and slow rotational speeds give rise to large vibration amplitudes and low vibration frequencies. This requires a monitoring system with special low frequency response capabilities.

In addition, many of the vibration behaviors typical to these machines require specialized filtering and signal conditioning. For example, rough load zone is known to generate vibration at sub-harmonic frequencies. By monitoring the overall vibration amplitude minus the 1X component, a parameter called NOT 1X is derived; it is a reliable indicator of rough load zone. Shear pin failures and wicket gate problems are known to generate primarily super-harmonic frequencies, known as NX frequencies, that are multiples of turbine running speed. By monitoring NX and a derived measurement (known as Composite) which consists of both gap voltage and NX amplitude, these faults can be detected. Various forms of electrical, hydraulic, and mechanical unbalance manifest themselves primarily as 1X vibration. Many other problems show up as simply an increase in overall vibration amplitude.

To address these specialized filtering, signal processing, and frequency response requirements, Bently Nevada has developed the 3500/46M Hydro Monitor module. A 4-channel monitor, channels can be configured for either air gap measurements or radial vibration measurements, simultaneously processing the input signal for each channel, depending on configuration, as follows:

RADIAL VIBRATION (Guide Bearings, Seal Ring Position, Blade Tip Clearance)	GENERATOR AIR GAP
• Overall vibration (direct) • 1X filtered vibration and phase • NX filtered vibration and phase (where N is a user-selectable integer between 2 and 20) • NOT 1X vibration amplitude • Gap voltage (shaft radial position) • Composite	• Instantaneous air gap • Average air gap • Minimum air gap • Maximum air gap • Minimum air gap pole number • Maximum air gap pole number

Users can establish Alert and Danger alarming on many of these parameters, and the monitor is fully compatible with System 1 software, allowing a variety of hydro-specific plots to be generated such as air gap versus pole, rotor shape, and combined rotor/stator shape for roundness and concentricity.

TABLE 2

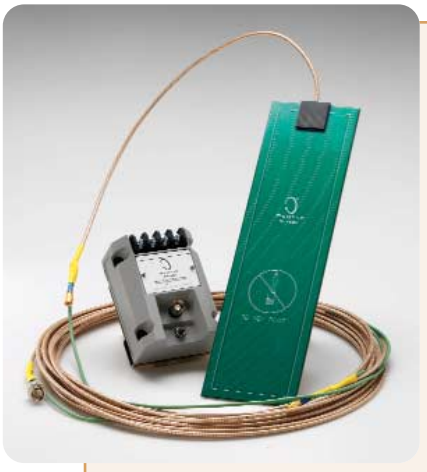
MEASUREMENT	MONITOR	TRANSDUCER
Guide Bearing Vibration (Runout) By measuring vibration at generator and turbine guide bearings, a variety of important malfunctions can be detected such as rough load zone*, various sources of unbalance, shear pin failure, bearing problems, and wicket gate problems. Each channel of the 3500/46M module can simultaneously monitor direct, 1X vector, NX vector, NOT 1X, shaft radial position (gap voltage), and composite amplitude (gap voltage change multiplied by NX amplitude). This special signal conditioning and filtering is required for detecting various malfunctions.	3500/46M 4-channel Hydro Monitor	3300 XL Series Proximity Transducer Targeting the Machine Shaft X-Y configuration at each bearing.
Thrust Bearing Oil Film Thickness Large vertical hydro units can weigh over 1,000 tons, with the unit's entire weight carried by the thrust bearing. An absence or reduction in oil film thickness at the thrust pads results in rapid breakdown of the bearing babbit and can result in rotor/bearing damage if not corrected. On hydro units, the thrust bearing shoes are fitted with proximity probes observing the thrust collar, providing a measurement of oil film thickness.	3500/40M or 3500/42M 4-channel Vibration / Position Monitor	3300 XL Series Proximity Transducer One probe each in two selected pads, with approximately 90 degrees of radial separation. For units larger than 100 MW, four probes (one every 90 degrees) are generally advised.
Guide Bearing Temperatures Bearing temperature can indicate problems related to fluid-film bearings, including overload, bearing fatigue, or insufficient lubrication.	3500/61 6-channel Temperature Monitor	RTD or Thermocouple One sensor per bearing pad.
Thrust Bearing Temperatures Bearing temperature can indicate problems related to fluid-film bearings, including overload, bearing fatigue, or insufficient lubrication.	3500/61 6-channel Temperature Monitor	RTD or Thermocouple One sensor per bearing shoe.
Keyphasor® Signal A proximity probe observing a once-per-turn notch or protrusion (such as a key or keyway) on the machine's shaft provides a precise reference signal used for indicating rotational speed, filtering vibration to multiples of running speed (such as 1X, NX, and NOT 1X), providing vibration phase information, and allowing air gap profile data. The Keyphasor signal is required by the 3500/46M and other monitor modules.	3500/25 Keyphasor® Module	3300 XL Series Proximity Transducer Generally mounted near the upper guide bearing. The shaft's notch or projection should align with an established reference on the rotor such as the generator's #1 pole.
Head Cover/Draft Tube Vibration Certain operating conditions can give rise to cavitation, an implosion of vapor cavities in the liquid. Cavitation can damage the turbine, eroding metal, affecting efficiency, and eventually forcing a shutdown and dewatering for repair of affected parts. Cavitation is measured with an accelerometer mounted on the draft tube or the turbine head cover. By monitoring for draft tube or head cover vibration with an accelerometer, and filtering appropriately, cavitation can be detected and conditions can be adjusted to avoid operating the unit in this damaging region.	3500/42M 4-channel Proximitor® / Seismic Monitor	330425 Accelerometer
Generator Air Gap Special capacitive sensors mounted around the bore of the stator measure the distance between the rotating and stationary parts in the generator. Air gap measurement is important because the stator is a flexible assembly that can become distorted or off center. The monitor is able to provide instantaneous, minimum, maximum, and average air gap measurements along with the rotor pole to which min and max measurements coincide. When connected to System 1, the software can interpolate between sensors, providing calculated stator shape plots.	3500/46M 4-channel Hydro Monitor	4000 Series Air Gap Sensor Four sensors per stator when bore diameter is less than 7.5m; eight sensors when bore exceeds 7.5m; 12-16 sensors when bore exceeds 12m.
Stator Frame Vibration Vibration of the stator core and frame can cause fretting and damage to the winding insulation. Uneven air gap can also cause the stator core to vibrate. By mounting an appropriate seismic vibration transducer on the stator core/frame, such problems can be detected before serious damage occurs.	3500/46M 4-channel Hydro Monitor	Low-frequency seismic transducers mounted on the outer diameter of the stator core and frame.
Generator Temperatures Temperature sensors are installed in locations such as in stator slots, air cooler inlet and outlet, water inlet and outlet, etc., providing important information on stator condition. The monitor provides alarming functions, alerting operators when temperatures are outside of acceptable limits. The monitor can also supply temperature information to System 1 software where it can be trended and correlated with other measurements for a more complete picture of unit health.	3500/61 6-channel Temperature Monitor	RTD or Thermocouple

** A United States patent is pending for detection of rough load zone operation.*

TABLE 2 (CONTINUED)

MEASUREMENT	MONITOR	TRANSDUCER
Process Variables Load, reactive load, exciter voltage and current, generator voltage and current, lube oil pressure, wicket gate position, and reservoir elevation are just a few of the parameters that may be available in the unit's or plant's control and automation system, and these variables can generally be easily interfaced to System 1 software. However, in some cases a process-related measurement is either not available in the unit's control system, or it is simply beneficial to hardwire the signal in parallel to both the control system and the condition monitoring system. Unit load is a particularly important parameter that should be included in the condition monitoring system whenever possible.	3500/62 6-channel Process Variable Monitor	Any sensor with an industry-standard proportional output of 4-20 mA, 1-5 Vdc, or any proportional voltage between –10 and +10 Vdc
Generator Partial Discharge Partial discharges are the small electrical sparks that occur within the voids of high-voltage insulation systems. By monitoring these partial discharges, a variety of winding-related problems can be detected, allowing maintenance to be planned and serious failures to be avoided.	Continuous PD monitor (provided by third party).	Capacitive PD Couplers
Wicket Gate Position Monitoring wicket gate position provides an indication of turbine flow. Combined with other parameters such guide bearing vibration, reservoir elevation, and load, flow-induced instabilities at the turbine runner can be identified and avoided. Wicket Gate position is often included in the unit's control system and can be monitored directly with System 1. If wicket gate position is not monitored, an LVDT can be used to make the measurement.	3500/45 4-channel Position Monitor	Linear Variable Differential Transducer (LVDT)
Seal Ring Position/Blade Tip Clearance Francis-, Kaplan-, and propeller-type turbines employ seal rings to prevent unwanted leakage of water past the runner, influencing efficiency. Francis units have two rings – a stationary ring and a rotating ring mounted on the runner. In contrast, Kaplan and propeller units have only a stationary ring that seals directly against the rotating blade tips. Mounted at the extremity of the unsupported portion of the shaft, these sealing surfaces are subject to rubbing when extreme shaft deflection occurs. On pump/storage units, such deflections can be common during pump-mode startup.	3500/46M 4-channel Hydro Monitor	3300 XL Series 11mm Proximity Transducer, modified for underwater use and runner target material.

(continued on page 56)



An All-New Air Gap Sensor System

Air gap is a measure of the distance between rotor and stator in the hydro generator. On-line monitoring of air gap is important because both the stator and the rotor on large hydro machines can be quite flexible, and their shape and location are affected by operating centrifugal, thermal, and magnetic forces.

Off-center or out-of-round conditions will, at minimum, reduce operating efficiency. More severe cases can lead to damage from magnetically induced heating or a rotor-to-stator rub.

Air gap monitoring utilizes multiple specially designed capacitive proximity sensors that are mounted on the inner bore of the generator stator in one or more planes. Measurements are made from the stator bore to each rotor pole as the rotor turns. Minimum air gap dimension and location along with rotor shape are directly measured during unit operation. Stator shape is calculated utilizing multiple air gap transducers.

Air gap measurements are made using Bently Nevada's 4000 Series Air Gap Sensor System and the 3500/46M monitor. Its unique design has a United States patent pending, and it incorporates many of the robust design features found in our eddy-current proximity probes used for vibration and position measurements, ensuring long, trouble-free service. Special focus has been placed on making the product easy to install, immune to installation-related performance variation, and robust for years of trouble free service.

To learn more, download the product datasheet from www.bently.com, or consult your nearest Bently Nevada sales professional.

(continued from page 55)

System 1® Software – An Optimization and Diagnostics Platform

By adding condition monitoring and diagnostics software to the hydro monitoring hardware, customers can take an important step forward in their ability to proactively manage their hydro units.

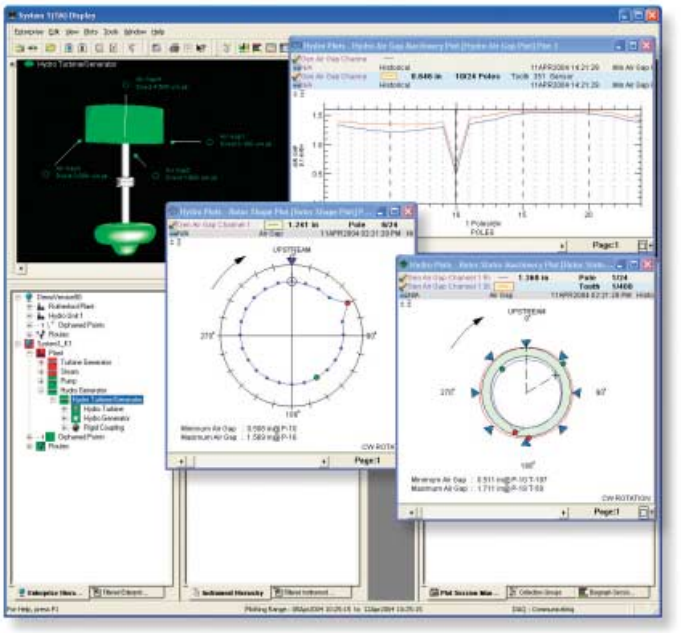
System 1 is a platform for managing every asset in your plant. In addition to its condition monitoring capabilities, System 1 links to maintenance management applications, reliability tools, process control, SCADA, historian systems, diverse documentation resources, and much more. This integration of multiple systems is a significant advantage to hydro customers, allowing them to monitor and trend parameters from diverse systems in a single user interface. And – as we'll discuss in the section on Decision Support – System 1 not only displays data, it *analyzes* data.

System 1 now includes powerful capabilities specifically for addressing the unique needs of hydroelectric turbine-generators. The result is a total hydro asset management solution capable of providing:

- Bearing babbit and oil temperature
- Air Gap
- Generator Stator Temperature
- Cavitation
- Seal Ring Clearance
- All available process variables
- Generator Partial Discharge
- Vibration monitoring over the entire operating frequency range
- Thrust bearing oil film thickness
- Stator core and frame vibration
- Wicket Gate Position
- Turbine flow monitoring

System 1 software allows you to analyze, trend, correlate, and display vibration, position, temperature, and any other variable of interest. A wide variety of plot types are available with relevance to hydro operators, a few of which are summarized in Table 3.

TABLE 3 >>



System 1 software features a vriety of new plot types specifically for hydro units.

NEW HYDRO-SPECIFIC PLOT TYPES IN SYSTEM 1

OVERALL HYDRO PLANT VIEW	Displays an overview of plant condition with normal parameters in green and alarm parameters in colors designating severity of the alarm.
AIR GAP PLOTS (GAP VERSUS POLE)	Displays the gap for each sensor versus pole number, for one rotor revolution.
AIR GAP PLOTS (ROTOR SHAPE)	Displays measured rotor shape as observed from each air gap probe.
AIR GAP PLOTS (COMBINED ROTOR AND STATOR SHAPE)	Displays stator and rotor roundness and concentricity by combining measured rotor shape with calculated stator shape.
X VERSUS Y	Plotting any X (such as vibration) versus any Y (such as unit load), provides powerful diagnostic tools. Cause-and-effect relationships and correlation can be easily visualized and understood. System 1 has data historian capabilities allowing it to archive virtually any data, even if not condition-related. It can also interface to existing historian systems you may already have installed.
MULTI-PARAMETER PLOTS	Multiple parameters can be displayed on the same plot. For example, plotting turbine flow, combined unit load, and bearing vibration provides the ability to immediately identify events associated with rough load zone. Changes in the duration and amplitude of these events can be an indication of excessive wear or impending failure.

Decision Support℠

A key aspect of asset management is the ability to detect asset-related symptoms and events as early as possible and with as much clarity as possible. This is where System 1 provides exceptional capabilities. In addition to System 1's powerful plotting, trending, and manual data analysis functionality is its Decision Support functionality. Decision Support is System 1's ability to automatically validate and analyze its collected data using user-configurable rules and knowledge; detect mechanical, electrical, or hydrodynamic problems; and generate informative Actionable Information® advisories.

Let's say that you want to customize the system with special rules reflecting a known set of conditions that, through experience, you've found always indicate a need for maintenance and are unique to a particular unit. For example, you have found that an increase in vibration at NX (where N is the number of wicket gates and X is operating speed) combined with a change in the rotor shaft position (lower guide bearing gap) and shaft orbit is an indication of a broken wicket gate shear pin.

When System 1 detects these three parameter changes based on your custom criteria, you might have multiple people in the plant that you want to notify. A different event notification message (with content completely customized to the recipient – even their name and phone number!) can be sent to each individual, with any severity you determine, using any of System 1's notification mediums (process control system alarm, e-mail, cell phone, PDA, pager, desktop software notifier, etc.).

System 1 RulePaks

We have also introduced a series of pre-configured rule collections – RulePaks – for specific machine types. In fact, a hydro-specific RulePak is currently in development. RulePaks can be loaded directly into the Decision Support module of System 1, giving you ready-made capabilities to automatically isolate and identify numerous common problems for specific machine types or even machine components, without the need to write your own rules.

RulePaks can also be combined with the rules you have authored yourself using Decision Support Studio, giving you a system tailored to your exact needs. Armed with these Decision Support capabilities, your company's ability to make faster, more confident operating and maintenance decisions is easier than ever.

Services – From Turnkey to Do-It-Yourself

Every customer is different. Some prefer to monitor their machines themselves and install the systems themselves. Others want help with installation, but not with the actual use of the system to perform machinery diagnostics. Still others may require occasional help with balancing or alignment, but little else. Whatever your needs, Bently Nevada is pleased to offer a comprehensive portfolio of services for hydro units, including:

- Monitoring system design, site installation, site project management, and full system documentation (both new machines and retrofits)
- System integration to ensure your condition monitoring system can interchange data and information with process control, SCADA, maintenance management, reliability management, and other pertinent systems
- Balancing and alignment
- Training – for both machinery diagnostic fundamentals and operation/maintenance of monitoring system instrumentation
- Reliability Services including Opportunity/Risk Assessment
- Lubrication consulting/management
- Foundation/footing problems
- Remote or onsite machinery diagnostics
- Condition monitoring program management
- Support for all Bently Nevada and selected other instrumentation and software solutions

Summary

Many of today's hydro units are operating under conditions that introduce significant mechanical and electrical stress on the assets – stresses that were often not even envisioned when the machines were designed, and stresses that are a direct result of new realities in the power market that require tremendous operational flexibility. Never before has the need for comprehensive condition monitoring on hydro units been more important, and Bently Nevada can now offer the hardware, software, and services to fully address these important assets. New transducers, new 3500 Series monitoring modules, new capabilities in System 1 software, and newly expanded service offerings – all designed to meet the unique needs of our hydro customers. For more information, contact your nearest Bently Nevada sales professional, or visit us on the Web at www.bently.com.